

# The first second of SN1987A neutrino emission

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## Abstract

A large fraction of SN1987A electron antineutrino events has been recorded in the first second. We study how this observation fits into the conventional paradigm for neutrino emission, and show that there is a  $3.2\sigma$  hint for an initial accretion phase. This phase involves a large fraction of the energy emitted in neutrinos and antineutrinos, about 20% or larger. The occurrence of neutrino oscillations strengthens these inferences. We discuss why three flavor oscillations with normal mass hierarchy are completely acceptable, whereas oscillations with inverted mass hierarchy require more troublesome interpretations, if  $\theta_{13}$  is above  $0.5 - 1^\circ$ .

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## 1 Context and motivation

The first second after a gravitational collapse is a moment of crucial importance. The very intense initial neutrino luminosity (denoted as ‘accretion’ in the following) is expected to have a non-thermal character [1], and it is thought to be the key to understand the subsequent explosion of the star [2, 3]. In this connection, it is very interesting to note that about 40% of the SN1987A events have been recorded in the first second: 6 out of 16 in Kamiokande-II [4], 3 out of 8 in IMB [5] and 2 out of 5

in Baksan [6] (the comparison is made with the number of events recorded in a window of  $T = 30$  seconds). This theoretical expectation and this experimental fact motivate us to analyze quantitatively the first second of SN1987A.

In our calculations we will largely follow Lamb and Loredó [7], who included for the first time a description of the background and of the time-energy distribution of the events. We will point out in the Appendix the technical points where we depart from their analysis. We will discuss the role of neutrino oscillations in the interpretation of the first second of SN1987A neutrinos and stress their importance.

## 2 Formulation of the problem

The parameter that we aim to study is the *fraction of energy* that was emitted in the non-thermal phase of neutrino emission, that occurred in (a fraction of) the first second. In formulae:

$$f_a \equiv \frac{\mathcal{E}_a}{\mathcal{E}_a + \mathcal{E}_c} \quad (1)$$

where the suffix  $a$  stays for ‘accretion’ (or non-thermal phase) and the suffix  $c$  for ‘cooling’ (or thermal phase). Strictly speaking, this fraction cannot be reconstructed completely from the observations, since in a very reasonable approximation we saw only electron antineutrinos. Thus, in order to fulfill the task, we must rely on some theoretical assumption here. We will assume unless stated otherwise that

$$\begin{cases} \mathcal{E}_a = 2 \times \mathcal{E}_a(\bar{\nu}_e) \\ \mathcal{E}_c = 6 \times \mathcal{E}_c(\bar{\nu}_e) \end{cases} \quad (2)$$

namely, we declare that the ratios between the total energy radiated  $\mathcal{E}$ , and the energy radiated in electron antineutrinos  $\mathcal{E}(\bar{\nu}_e)$  is 2 for the accretion and 6 for the cooling phase. These numbers are crucial for the interpretation of the result, so let us pause to discuss them before continuing. 1) The first fraction describes the assumption that during accretion only  $\nu_e$  and  $\bar{\nu}_e$  are radiated in equal amount due to  $ep \rightarrow n\nu_e$  and  $e^+n \rightarrow p\bar{\nu}_e$ . It does not seem implausible that the  $\nu_e$  are even more abundant than the  $\bar{\nu}_e$  during accretion, or that some other species of (anti)neutrinos are also radiated. In other words, the factor 2 could be an underestimation, and thus the fraction  $f_a$  that we estimate from the electron antineutrino data can be regarded as a reasonable value (or lower bound). 2) The second fraction is just the usual and often adopted “equipartition” hypothesis. Only if there is a large amount of energy radiated in non-electronic neutrinos (say,  $\mathcal{E}_c/\mathcal{E}_c(\bar{\nu}_e) \sim 10$  or larger) it could be possible to diminish significantly the ratio  $f_a$  and modify somewhat the conclusions that we will describe later in this paper.

In the rest of this section we discuss the tools that we use for a quantitative evaluation of  $\mathcal{E}_a(\bar{\nu}_e)$  and  $\mathcal{E}_c(\bar{\nu}_e)$  from SN1987A neutrino data: first of all, we give a description of the antineutrino flux, then we model the expected signal rate, and finally, we discuss the likelihood function that we adopt.

### 2.1 Parameterized antineutrino flux

Let us describe the adopted form of the parameterized neutrino fluxes (differential in the energy). We follow the one proposed in [7]:

$$\Phi_{\bar{\nu}_e}(t, E_\nu) = \frac{1}{4\pi D^2} \frac{\pi c}{(hc)^3} \left[ \frac{\varepsilon(t) Y_n M_a}{m_n} \sigma_{e+n}(E_\nu) g(E_\nu, T_a) + 4\pi R_c^2 g(E_\nu, T(t)) \right] \quad (3)$$

where  $g(E, T) = E^2/(1+\exp(E/T))$ . This describes an isotropic emission from a distance of  $D = 50$  kpc. The first term is given by the product of the number of targets (neutrons, with  $Y_n = 0.6$ ) in the accreting mass  $M_a$ , times the thermal distribution of positrons  $g$  (with average temperature  $T_a$ ), times the cross section of positron interactions, that increases quadratically with  $E_\nu$  and thus gives a non-thermal character to the emitted  $\bar{\nu}_e$ . The second term is instead a standard black body emission from a sphere with radius  $R_c$ . The time scales of the two processes of accretion and cooling ( $\tau_a$  and  $\tau_c$ ) appear in the functions:

$$\begin{cases} \varepsilon(t) = \frac{\exp[-(t/\tau_a)^{10}]}{1+t/(0.5 \text{ s})} \\ T(t) = T_c \exp[-t/(4\tau_c)] \end{cases} \quad (4)$$

Thus, we have 6 parameters (3 for each phase):  $M_a$ ,  $T_a$  and  $\tau_a$  for accretion;  $R_c$ ,  $T_c$  and  $\tau_c$  for cooling. For any set of values of these parameters, it is straightforward to calculate the energy carried by antineutrinos during accretion and during cooling, denoted by  $\mathcal{E}_a(\bar{\nu}_e)$  and  $\mathcal{E}_c(\bar{\nu}_e)$ .<sup>1</sup> In this way, using eq. 2, we can evaluate the value of  $f_a$ .

## 2.2 Signal rate

The signal rate, differential in time, positron energy  $E_e$  and cosine of the angle  $\theta$  between the antineutrino and the positron directions is:

$$S(t, E_e, \cos \theta) = N_p \frac{d\sigma}{d \cos \theta}(E_\nu, \cos \theta) \eta_d(E_e) \xi_d(\cos \theta) \Phi_{\bar{\nu}_e}(t, E_\nu) \frac{dE_\nu}{dE_e} \quad (5)$$

where  $N_p$  is the number of targets (free protons) in the detector,  $\sigma$  is the  $\bar{\nu}_e + p \rightarrow n + e^+$  (inverse beta decay) cross section,  $\eta_d$  the detector dependent average detection efficiency,  $\xi_d$  is the angular bias =1 for Kamiokande-II and Baksan whereas for IMB  $\xi_d(\cos \theta) = 1 + 0.1 \cos \theta$  [8], finally  $\Phi_{\bar{\nu}_e}$  (the electron antineutrino flux differential in the antineutrino energy  $E_\nu$ ) is as in eq. 3. The expression of the antineutrino energy  $E_\nu$  as a function of  $E_e$  and  $\cos \theta$  is given in the Appendix. Later we will use the shorthands by  $S(t, E_e) = \int S(t, E_e, \cos \theta) d \cos \theta$  and  $S(t) = \int S(t, E_e) dE_e$ .

## 2.3 The assumed likelihood

We estimate the parameters by evaluating:

$$\chi^2 = -2 \sum_{d=k,i,b} \log(\mathcal{L}_d) \quad (6)$$

where  $\mathcal{L}_d$  is the likelihood of any detector ( $k, i, b$  are shorthands for Kamiokande-II, IMB, Baksan). We use Poisson statistics. Dropping constant (irrelevant) factors, the unbinned likelihood of the three detectors are:

$$\mathcal{L}_d = e^{-f_d \int_{-t_d}^T S(t+t_d) dt} \prod_{i=1}^{N_d} e^{S(t_i+t_d)\tau_d} \left[ \frac{B_i}{2} + \int S(t_i + t_d, E_e, c_i) G_i(E_e) dE_e \right] \quad (7)$$

where of course the dependence on the 6 model parameters is contained in  $S$ . Each detector saw  $N_d$  events; their time, energy and cosine with supernova direction are called  $t_i$ ,  $E_i$  and  $c_i$  ( $i = 1 \dots N_d$ ).

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<sup>1</sup>We get  $\mathcal{E}_a = 4.14 M_a T_a^6 \tau_a \varphi$  and  $\mathcal{E}_c = 3.39 \cdot 10^{-4} R_c^2 T_c^4 \tau_c$  measuring  $\mathcal{E}_{a,c}$  in foe ( $= 10^{51}$  erg),  $M_a$  in  $M_\odot$ ,  $R_c$  in km,  $T_{a,c}$  in MeV and  $\tau_{a,c}$  in seconds;  $\varphi \equiv \int_0^\infty dx \exp(-x^{10})/(1+x \tau_a/0.5) \sim 0.6$  in the relevant  $\tau_a$  range.

The time is counted from the first detected event; namely, we set  $t_1 \equiv 0$  for all detectors. The integral over the time in the first exponential factor is performed from the moment when the first neutrino reaches the Earth  $t = -t_d$  (where  $t_d \geq 0$ ), till the end of data taking,  $t = T$  with  $T = 30$  s. The values of the 3 new parameters  $t_d$ , called ‘offset times’, are estimated together with model parameters by fitting the data (and, *a posteriori* found to be small) since the measurement of the absolute times in Kamiokande-II and Baksan are not reliable. In IMB, the live time fraction is  $f_d = 0.9055$  and the dead time is  $\tau_d = 0.035$  s, whereas for the other detectors  $f_d = 1$  and  $\tau_d = 0$ . The specific background rate is  $B_i = B(E_i)$  as discussed in [9] and in the Appendix (we denote by  $B(E_e)/2$  the background distribution, differential in time, energy and cosine—the factor 1/2 is for an uniform cosine distribution). The Gaussian distribution  $G_i$  includes the estimated values of the energy  $E_i$  and the error of the energy  $\delta E_i$  for any individual event; the inclusion of the error on the measurement of  $\cos \theta$  does not add significant information, and the relative time of any event is precisely measured.

### 3 Results of the analysis

In this section we present the results of our statistical analysis. For reasons of clarity and for a more direct comparison with previous results, we will ignore the occurrence of neutrino oscillations in the first part of this section; in practice, the results that we obtain can be regarded as the best ‘effective antineutrino flux’ that describes the data. In the second part of this section, we will consider the modifications due to the occurrence of neutrino oscillation, and discuss why certain cases with inverted mass hierarchy are disfavored by SN1987A data.

#### 3.1 Fraction of energy in the accretion phase

First of all, we searched the global minimum of the  $\chi^2$ . The best fit of the initial accreting mass  $M_a \sim 5 M_\odot$  is not physically plausible, since we expect that the mass exposed to positrons will be *at most* the mass of the whole outer core  $\sim 0.6 M_\odot$ . Thus, we analyzed the  $\chi^2$  as a function of  $M_a$ . For a wide range of values of  $M_a$  we marginalized away the remaining 8 parameters by minimizing the  $\chi^2$  (normalized as usual to the best fit point) and obtained in this way fig. 1. From fig. 1 we conclude that: (i) Although larger masses would fit the data better, a completely reasonable value of the outer core mass,  $M_a = 0.5 M_\odot$ , is not significantly disfavored in comparison to the best fit value. This justifies the fact that we adopt this value for reference in a large part of this paper, rather than the best fit value.<sup>2</sup>

(ii) There is a significant hint for an accretion phase. In fact, let us ask whether the improvement going from  $M_a = 0$  (no accretion) to  $M_a = 0.5 M_\odot$  is simply due to the presence of the two new variables  $T_a$  and  $\tau_a$  (*i.e.*, let us perform a likelihood ratio test with two degrees of freedom). We find that we can reject the null hypothesis in favor of the hypothesis that accretion occurred with a significance of  $\alpha = 1.2 \times 10^{-3}$ , *i.e.*,  $3.2\sigma$  in Gaussian language.

(iii) Even small values of  $M_a$  are able to improve significantly the fit to SN1987A data. In fact, when  $M_a$  decreases, the best fit value of the temperature  $T_a$  increases, as one can read clearly from table 1. Keeping in mind eq. 3, one understands that the number of events during accretion scales as  $M_a \times T_a^{6-8}$ , so that small changes of  $T_a$  are able to ‘compensate’ the decrease in  $M_a$ . A similar argument applies also to the values of the accretion energy  $\mathcal{E}_a$  and of the energy fraction  $f_a$ , that, as we can see from

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<sup>2</sup>This argument and this conclusion is in agreement with what found in [7].

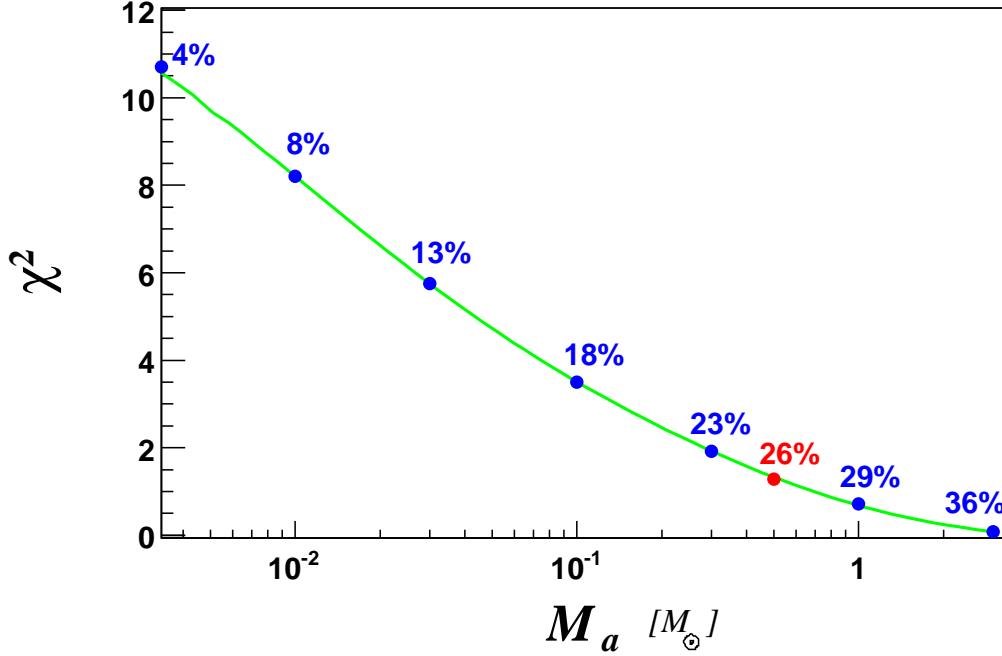


Figure 1: Values of  $\chi^2$  as a function of the initial accreting mass  $M_a$  in units of solar mass. Also indicated the corresponding values of  $f_a$  for the reference case  $M_a = 0.5M_\odot$  and for the cases selected in table 1. For  $M_a = 0$  (no accretion)  $\chi^2 = 14.7$ .

table 1 and fig. 1, react slowly to important changes of  $M_a$ .

(iv) Finally, a value smaller than  $M_a = 0.01M_\odot$  is disfavored at about 99% in comparison to the one we selected.

Now we consider the outcome of the fit in the point  $M_a = 0.5 M_\odot$ . The best fit of the offset times is zero. Their 1 sided,  $1\sigma$  errors (obtained by integrating the marginalized likelihood) are:

$$\Delta t_{\text{KII}} = 0.09 \text{ s}, \quad \Delta t_{\text{IMB}} = 0.31 \text{ s}, \quad \Delta t_{\text{Baksan}} = 0.25 \text{ s} \quad (8)$$

similar results remain valid also with oscillations. The values of the 6 astrophysical parameters that we find from our statistical analysis along with the  $1\sigma$  errors (obtained instead by a conventional,  $\Delta\chi^2 = 1$ , Gaussian procedure) are:

$$\begin{aligned} M_a &\equiv 0.5 M_\odot, & T_a &= 2.0 \pm 0.1 \text{ MeV}, & \tau_a &= 0.70^{+0.17}_{-0.21} \text{ s} \\ R_c &= 12^{+6}_{-4} \text{ km}, & T_c &= 5.5 \pm 0.8 \text{ MeV}, & \tau_c &= 4.4^{+1.5}_{-1.0} \text{ s} \end{aligned} \quad (9)$$

The temperature of the electrons  $T_a$  is pretty low; this outcome of the fit is simply due to the fact that the early Kamiokande-II events have low energy [9]. The duration of the accretion phase is rather close to the expectations, about half a second, [2, 3] and [10]. Coming to the parameters of the cooling phase, we see that the radius of neutrino-sphere is rather similar to the radius of the neutron star, as expected (see *e.g.*, [11]). The temperature  $T_c$  implies an initial average energy  $3.15T_c$  and an average

$M_a$ [ $M_\odot$ ]	$T_a$ [MeV]	$\tau_a$ [s]	$\mathcal{E}_a$ [ $10^{52}$ erg]	$R_c$ [km]	$T_c$ [MeV]	$\tau_c$ [s]	$f_a$ [%]
0.003	3.7	0.69	<b>1.2</b>	19	4.6	4.7	<b>4</b>
0.01	3.3	0.69	<b>2.0</b>	15	4.9	4.8	<b>8</b>
0.03	2.9	0.69	<b>2.9</b>	13	5.1	4.7	<b>13</b>
0.1	2.5	0.69	<b>4.0</b>	12	5.3	4.6	<b>18</b>
0.3	2.2	0.70	<b>5.4</b>	12	5.4	4.4	<b>23</b>
1.0	1.9	0.71	<b>7.6</b>	12	5.5	4.3	<b>30</b>
3.0	1.6	0.72	<b>10.</b>	12	5.5	4.1	<b>36</b>

Table 1: *The astrophysical parameters of neutrino emission defined in eqs. 3 and 4, calculated for selected values of  $M_a$ . In boldface the derived quantities defined in eqs. 1 and 2.*

value 3/4 lower, namely,  $12.9 \pm 1.9$  MeV, which compares well with the expectations [12, 13]. Finally, the duration of the cooling phase is brief, *e.g.*, when compared with the 20 seconds estimated in [1] though this leads to a reasonable value of the total emitted energy  $2.4 \times 10^{53}$  erg, that compares well with the one expected for neutron star formation [14].<sup>3</sup>

With the parameters in eq. 9 it is straightforward to calculate the amount of energy emitted during accretion, during cooling, and the energy fraction  $f_a$ :

$$\begin{cases} \mathcal{E}_a = 6.1 \times 10^{52} \text{ erg} \\ \mathcal{E}_c = 1.8 \times 10^{53} \text{ erg} \end{cases} \Rightarrow f_a(\text{no osc.}) = 26\% \quad (10)$$

It is interesting to note that the central value of  $f_a$  estimated from the fit is two-three times larger than the expected one [15] (see also [16]). Other values of  $f_a$  are considered in table 1 and correspond to the points marked in figure 1.

### 3.2 Impact of neutrino oscillations

We will assume that the temperature of the muon and tau antineutrinos (that are implied in the cooling phase) are in a fixed ratio with the  $\bar{\nu}_e$  temperature. Following [13], we will take as default value

$$T(\bar{\nu}_\tau)/T(\bar{\nu}_e) = T(\bar{\nu}_\mu)/T(\bar{\nu}_e) = 1.2 \quad (11)$$

As stated above, we also assume that in the accretion phase muon or tau (anti) neutrinos are absent or very rare and discuss the role of this assumption later.

**Formalism** Considering oscillations among the usual three neutrinos, the observed electron antineutrino fluxes are:

$$\Phi_{\bar{\nu}_e}^{osc} = P \Phi_{\bar{\nu}_e} + (1 - P) \Phi_{\bar{\nu}_\mu} \quad (12)$$

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<sup>3</sup>The total number of events *seen* / **expected** in 30 seconds (in brackets the background events) is:  $N_{\text{KII}} = 16$  / **20.0** (5.6),  $N_{\text{IMB}} = 8$  / **6.0** (0.0),  $N_{\text{Baksan}} = 5$  / **2.5** (1.0)

where it is assumed that  $\Phi_{\bar{\nu}_\mu} = \Phi_{\bar{\nu}_\tau}$ . The expression of the electron neutrino survival probability  $P$ , that keeps into account the matter effect [17, 18], is:

$$P = \begin{cases} U_{e1}^2 & \text{for **normal** mass hierarchy} \\ U_{e1}^2 P_f + U_{e3}^2 (1 - P_f) & \text{for **inverted** mass hierarchy} \end{cases} \quad (13)$$

where we have to distinguish the two arrangement of the neutrino mass spectrum compatible with present knowledge of neutrino oscillations (see *e.g.* [19]). We adopt the conventional decomposition of the mixing elements in terms of the mixing angles:  $U_{e3} = \sin \theta_{13}$  and  $U_{e1} = \cos \theta_{12} \cos \theta_{13}$ . We see that in the case of normal mass hierarchy, the probability  $P \sim 0.7$  is reliably predicted and rather precisely known. Instead, for inverted mass hierarchy,  $P$  depends strongly on the unknown mixing angle  $\theta_{13}$ . In fact, the so called flip probability  $P_f$  (that quantifies the loss of adiabaticity at the ‘resonance’ related to the atmospheric  $\Delta m^2$ ) is:

$$P_f(E_\nu, \theta_{13}) = \exp \left[ -\frac{U_{e3}^2}{3.5 \times 10^{-5}} \times \left( \frac{20 \text{ MeV}}{E_\nu} \right)^{2/3} \right] \quad (14)$$

where the numerical value corresponds to the supernova profile  $N_e \sim 1/r^3$  given in [18]. For the measured solar oscillation parameters, the Earth matter effect is expected to be pretty small [20], and we will neglect it in the rest of the analysis.

**Results for normal hierarchy** A fit to the data, made in the same way as for eq. 9 but accounting for oscillations with normal mass hierarchy yields:

$$\begin{aligned} M_a &\equiv 0.5 M_\odot, & T_a &= 2.1 \pm 0.1 \text{ MeV}, & \tau_a &= 0.70_{-0.20}^{+0.19} \text{ s} \\ R_c &= 13_{-5}^{+8} \text{ km}, & T_c &= 5.1_{-0.7}^{+0.9} \text{ MeV}, & \tau_c &= 4.4_{-1.1}^{+1.5} \text{ s} \end{aligned} \quad (15)$$

The correlation coefficients  $\rho(x, y) = \sigma(x, y) / (\sigma(x)\sigma(y))$ , in percent (%), are:

$$\begin{aligned} \rho(T_c, R_c) &= -89, & \rho(T_c, \tau_c) &= -42, & \rho(T_a, \tau_a) &= -16, & \rho(T_a, \tau_c) &= 11, & \rho(\tau_c, R_c) &= 9, \\ \rho(R_c, T_a) &= -9, & \rho(\tau_c, T_a) &= 4, & \rho(T_c, \tau_a) &= -3, & \rho(T_c, T_a) &= 1, & \rho(R_c, \tau_a) &= 0. \end{aligned}$$

The larger ones correlate the parameters of the cooling phase (a well-known result). The coefficients that correlate the phases of cooling and accretion are instead small.

The  $\chi^2$  increases by  $\Delta\chi^2 = 0.8$ , namely, it does not change significantly. In other words, we claim that in the context of the discussion *SN1987A data alone do not provide us with a strong sensitivity to oscillations with normal mass hierarchy*. This can be understood as follows. The main impact of oscillation is on the neutrinos emitted during accretion; in fact, the flux of antineutrinos is multiplied by  $P \sim 0.7$ . This means that the expected number of events during accretion is the same that we found without oscillations, for a value of  $M_a = P \times 0.5 \sim 0.35$ . From table 1 and figure 1 we see that this case has a perfectly acceptable  $\chi^2$ , that concludes the explanation. However, the fraction of energy emitted during accretion does not diminish with the oscillations, because even if 30% of the antineutrinos become invisible to inverse beta decay reaction, they should be anyway produced. In fact, the higher temperature  $T_a$  implies that  $f_a$  increases:

$$\begin{cases} \mathcal{E}_a = 8.1 \times 10^{52} \text{ erg} \\ \mathcal{E}_c = 1.7 \times 10^{53} \text{ erg} \end{cases} \Rightarrow f_a(\text{osc., n.h.}) = 32\% \quad (16)$$

compare with eq. 10. Eq. 10 is the main result of our analysis, and will be discussed in detail later.

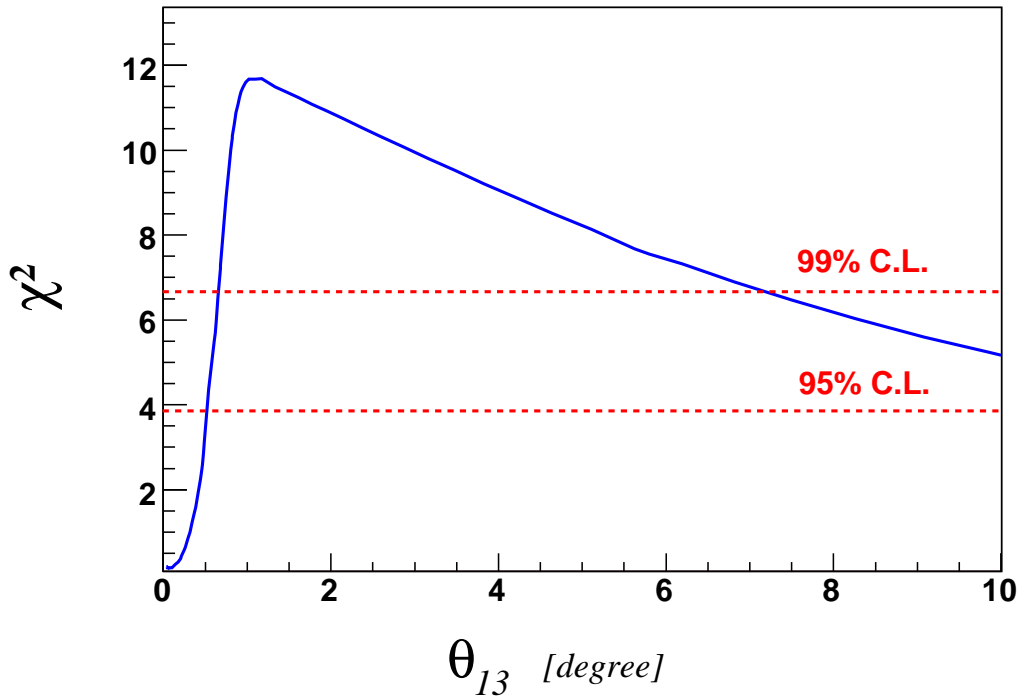


Figure 2: The  $\chi^2$  for the hypothesis of inverted mass hierarchy and for values of  $\theta_{13}$  allowed by present knowledge of oscillations. See text for discussion and warnings.

**Results for inverted hierarchy** The case of inverted mass hierarchy can produce  $P \sim 0$  and thus a strong suppression of the electron antineutrino flux during accretion. This can be seen clearly from figure 2, where (fixing  $M_a = 0.5M_\odot$ ) we give the value of the  $\chi^2$  for various values of  $\theta_{13}$  that are allowed by what we know at present on oscillations. Thus, the conventional treatment of oscillations in eq. 13 implies that the high-luminosity feature visible in the first second of emission disfavors the case when neutrinos have an inverted mass hierarchy and values of  $\theta_{13}$  larger than  $0.5^\circ - 1^\circ$ . It should be noted that for the largest value of  $\theta_{13}$  the fit improves, but the price to pay is a very large amount of energy emitted during accretion; *e.g.*, for  $\theta_{13} = 10^\circ$  we need  $\mathcal{E}_a = 7.7 \times 10^{53}$  erg  $>$   $\mathcal{E}_c = 2.1 \times 10^{53}$  erg! This can be seen as an indication against the case of inverse mass hierarchy and relatively large values of  $\theta_{13}$ . This result is surely interesting, but in our opinion it should be taken with caution due to:

1. Limited astrophysical information. Indeed, in presence of a relevant muon/tau antineutrino emission during accretion, the effect of oscillation weakens (at the same time the fraction  $f_a$  increases, see eq. 2 and discussion therein).
2. Possible modifications of physics of oscillation. Indeed, neutrino contribute to weak (‘matter’) potential, especially during accretion, making the problem non-linear [21].

Our treatment of oscillation conforms to the conventionally accepted framework and develops in the context of eq. 2. This is the best that we can do at present; once the modifications from points 1. and 2. above will be precisely quantified, it will be a straightforward exercise to repeat these steps to know whether these results change significantly.

However, it is interesting to try to explore what could happen by relaxing the assumptions we followed till now, and this is what we attempt in the last part of this section. For definiteness, let us ask what happens if  $P = \kappa$  with  $\kappa = 0.1$  or  $= 0.5$ . The fit is similar to the one corresponding to  $M_a = P \times 0.5M_\odot$  in table 1 (thus acceptable on the basis of  $\chi^2$ ) however we would need to emit during accretion an energy  $1/P$  times larger than the one we read from table 1. More in details, we find  $\mathcal{E}_a = 3.3 \times 10^{53}$  erg for  $\kappa = 0.1$  and  $\mathcal{E}_a = 1.0 \times 10^{53}$  erg for  $\kappa = 0.5$ . The first case can be questioned on theoretical basis, whereas the second, that leads to  $f_a = 36\%$ , seems much more reasonable. This means that if non-linear effect are able to produce an effective survival probability  $P \sim 0.5$ , inverted neutrino oscillations will be not in serious disagreement with SN1987A observations. Comparing with eq. 12, we see that the two case here considered are similar to the case  $P \sim 0$  (*i.e.*, oscillations conforming to the conventional expectations) but with a flux of non-electronic neutrinos during accretion  $\Phi_{\bar{\nu}_x} = \kappa \times \Phi_{\bar{\nu}_e}$ . However, the estimated values of  $\mathcal{E}_a$  should be increased by the factor  $1 + 2\kappa$  due to the presence of non-electronic species during accretion. We conclude that within the conventional theoretical framework, we can have a good fit of SN1987A neutrinos only with important modifications of the hypothesis on the flavor composition of the neutrino flux during accretion (eq. 2) and/or with a strong modification of the oscillation probabilities shown in eq. 13. These effects could save the inverted hierarchy case, but would not change the conclusion on  $f_a$ , that can only increase in comparison with the case when oscillations are neglected and presumably also with the case of oscillations with normal mass hierarchy.

### 3.3 Expected range of $f_a$ and stability of the result

From here on, we focus on the case of oscillation with normal hierarchy; similar conclusions apply in the case of inverted with small  $\theta_{13} < 1^\circ$  (that becomes indistinguishable from the previous one for very small values of  $\theta_{13}$ ) and also without oscillations.

We evaluated the expected range of  $f_a$  in eq. 16 as follows:

- i) First we found the impact of  $M_a$ . By considering the  $\chi^2(M_a)$  allowed by the data (as in fig. 1) we obtain a corresponding range for  $f_a$ . We find that  $f_a > 18\%$  at 95% C.L.
- ii) Next, we found the effect of the other 5 astrophysical parameters. By propagating the errors, we obtain the absolute error  $\delta f_a = 10\%$ . This means that  $f_a > 16\%$  at 95% C.L.

The large errors are due to the fact the the number of events occurring during accretion is only about  $10^4$ .

We also checked the stability of our results on  $f_a$ :

- a) By shifting the offset times within their error-bars.
  - b) By considering alternative, reasonable parameterizations of the antineutrino flux such as those proposed and studied by [7].
  - c) By removing some event from the dataset (*e.g.*, when this is done with the event number 10 of Kamiokande-II—see [9]—the  $\chi^2$  somewhat improves).
- In none of these cases, however, our conclusion on  $f_a$  does change significantly. The reason is simply that this result is not due to an *ad hoc* statistical analysis, but to two clear experimental facts:
- 1) there is a relatively large number of events in the first second, especially in Kamiokande-II dataset;
  - 2) their energy is relatively low: compare with Sect. 3.2.3 of [9].

In conclusion, the data suggest that a considerable fraction energy was emitted during accretion. Though it is possible to have a smaller  $f_a$  for certain values of the astrophysical parameters of the neutrino emission that permit a reasonable description of the data, the fact that these parameters are not known at present and the occurrence of oscillations suggest that  $f_a$  was 20% or larger.

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<sup>4</sup>This will be certainly much larger when we will observe the neutrinos from a galactic supernova.

## 4 Discussion

We showed that data from SN1987A imply at  $3.2\sigma$  the existence of an initial phase of intense neutrino luminosity, that resembles what is expected during accretion. The agreement of the various astrophysical parameters with expectations is rather good, but there is a hint that the amount of energy emitted during accretion is a few times larger than what is expected in standard calculations. The significance of this hint is limited by the small number of detected events, but at the same time, it is a stable outcome of the analysis and it is due to clear features of the data (especially, those of Kamiokande-II). This result is not contradicted but rather reinforced if three flavor oscillations of neutrinos occurred with normal mass hierarchy (see eq. 16 and discussion therein). Instead, it is not easily reconciled with oscillations, if the mass hierarchy is inverted and  $\theta_{13}$  is larger than about  $1^\circ$ .

Let us comment these results. The first implication regards the nature of the explosion. We feel motivated to propose the speculation that a value  $f_a \sim 20\%$  (or larger) is a characteristic aspect of successful supernova explosions. It will be interesting to see whether such an expectation, driven by SN1987A data, will meet the findings of future successful simulations of supernova explosions: see [22] for a status report.

The second implication regards neutrino oscillations. We showed that a large oscillation effect on electron antineutrinos (*i.e.*, a small survival probability  $P$  in eq. 12) is disfavored by the data, since it would tend to dilute the number of events expected in the first second. This result should be taken with caution, since it is possible to argue that the expectations on flavor partition during accretion are not completely reliable, and/or that the oscillation could have a non-conventional character [21]. We believe that it is urgent to clarify this issue, for such a result could have important implications for several future experiments (such as long-baseline experiments, double beta decay search, cosmology [19]).

Of course, the most important task is left for the future supernova neutrino experiments, that should study precisely the first second of supernova explosion: in particular, the number of the events and their energy. It would be interesting to monitor the total flux of neutrinos in the first second, *e.g.* counting neutrons in a heavy water detector as SNO by  $\nu D \rightarrow \nu p n$ . However, it seems fair to conclude that the traditional method of investigation (namely, the observation of supernova electron antineutrino by inverse beta decay in scintillators or water Čerenkov detectors, possibly allowing for improvements in neutron detection) has still a bright future.

In conclusion, we presented a state-of-art analysis of the first second of SN1987A neutrino emission. We hope that this can be useful to understand better what happened in this crucial moment of neutrino astronomy and, possibly, to make further steps toward the theory of supernova explosion.

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## A Peculiarities of the analysis

As recalled, our analysis is similar to the one of Lamb and Loredó [7], with whom we agree within errors when we strictly stick to their procedure. The analysis that we eventually adopted in this paper departs from their one for the inclusion of oscillations, and for some technical points that we describe here:

1) *Background*: Lamb and Loredó fold the *measured* background curve with the distribution of the energy distribution of the events. However, this has the effect of double counting the detector-dependent effects on energy measurement, for which the detected energy is distributed around the true energy (‘smearing’). Thus, we prefer to directly use the background curve, setting  $B_i = B(E_i)$ ; namely, we do not perform any folding. This has the consequence that the events of Kamiokande below 7 MeV have a higher background rate, and those above 9 MeV a lower background rate, while the other ones stay almost unchanged. The changes for Baksan are instead negligible. See [9], Appendix A.

2) *Cross section*: When evaluating the signal rate  $S$  (eq. 5) we adopt the inverse beta decay cross section calculated in [24]. We use the expression for the cross section  $d\sigma/d\cos\theta$  given in eq. (20) there. The energy of antineutrino is given in term of the positron energy  $E_e$  and the angle  $\theta$  between the antineutrino and the positron directions:

$$E_\nu = \frac{E_e + \delta}{1 - (E_e - p_e \cos\theta)/m_p}, \quad (17)$$

where  $\delta = (m_n^2 - m_p^2 - m_e^2)/(2m_p) \approx 1.294$  MeV. We replace  $\cos\theta$  in the previous equation with the measured values for the first 12 Kamiokande-II and for the 8 IMB events, and set instead  $\cos\theta = 0$  for the 5 events of Baksan and the last 4 events of Kamiokande-II.

3) *Efficiency*: Following [7], we average the signal  $S$  as a function of the true value of the energy  $E_e$  over its distribution (assumed to be Gaussian); namely, we keep into account the energy smearing of the signal: see eq. 7. But differently from [7], we include also the detection efficiency as a function of the true energy of the event: see eq. 5. With this procedure, we describe the fact that the expected numbers of signal events (*i.e.*, the crucial input of the likelihood) should include all relevant detector dependent features (such as loss of events due to light attenuation, fluctuations of the number of photoelectrons, detector geometry, etc) including those that lead to an imperfect ( $\eta_d < 1$ ) detection efficiency.<sup>5</sup> We argue in favor of our procedure by considering the following situation. Imagine two detectors where the signal interaction rate is equal to the background rate, that differ by the detector efficiency:  $\eta = 100\%$  in the first one,  $\eta = 10\%$  in the second. Now, suppose that each of them observes an event. According to the procedure in [7], the probability that the observed event is due to a signal is 50% in both detectors (see table IV and discussion therein), that we find paradoxical. Instead, adopting our procedure the probability that the event is due to signal is 50% in the first detector and 9% in the second one, which seems to us more reasonable.

*Impact of the modifications*: The most important effect is the inclusion of the efficiency of detection, followed by the new cross section and finally by our assumption on the background. *E.g.*, adopting the procedure of [7] the temperature parameter  $T_c$ , the radius  $R_c$  and the time constant  $\tau_c$  of an exponential cooling model (as in eq. 3 but with  $M_a = 0$ ) are 3.7 MeV, 44 km and 4.4 s. When we include the efficiency, they become 4.2 MeV, 30 km and 3.9 s. When we use also the new cross section (eq. (25) in [24]) they become 4.6 MeV, 26 km and 3.7 s, and when we include the dependence on the  $\cos\theta$  (eq. (20) in [24]), these values become 4.5 MeV, 27 km and 3.8 s. Finally, with the new background all quantities stay practically unchanged.

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<sup>5</sup>We have in mind an ‘average efficiency’ evaluated by a MC procedure, namely 1) by simulating several events with *true* energy of the positron  $E_e$  but located in the various positions and emitted in all possible directions, and then 2) counting the fraction of times that an event is recorded and finally 3) deducing also the smearing on the energy (=average error as a function of  $E_e$ ). For an even more refined analysis of SN1987A data, one should evaluate for any individual event the specific detection efficiency and background rate [7, 9]. In our understanding, such a correction on individual basis was performed only to assess the errors on the energies of the events, see [4].

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